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X-641-73-350

PREPRINT

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NASA TM X 70521

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(NASA-TM-X-70521) POSSIBLE EVIDENCE FOR
STRUCTURED ACCELERATION OF COSMIC RAYS ON
A GALACTIC SCALE FROM RECENT GAMMA RAY
OBSERVATIONS (NASA) 13 p HC #3.00
14

N74-12456

CSCL 03B G3/29

Unclas
22459

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NOVEMBER 1973

Astrophysical Journal Letters
in press, 1974

GSFC

— GODDARD SPACE FLIGHT CENTER —
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POSSIBLE EVIDENCE FOR STRUCTURED ACCELERATION
OF COSMIC RAYS ON A GALACTIC SCALE FROM
RECENT γ -RAY OBSERVATIONS

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Received 1973 November 19

ABSTRACT

Recent data from SAS-2 on the galactic γ -ray line flux as a function of longitude reveals a broad maximum in the region of $|\ell| \lesssim 30^\circ$. This data, as unfolded here, implies that the low-energy (1-10 GeV) galactic cosmic-ray flux varies with the radial distance, ϖ , from the galactic center and is about an order of magnitude higher than the local value in a toroidal region for ϖ between 4 and 5 kpc. We further show that this enhancement can be plausibly accounted for by Fermi acceleration^{and compression}/caused by a hydrodynamic shock driven by the expanding gas in the "3 kpc" arm and invoked in some versions of galactic structure theory.

I. ENERGY SPECTRUM OF GALACTIC γ -RAYS.

Recently, Kniffen, et al. (1973) have reported results of observations of galactic γ -radiation above 30 MeV obtained from the second Small Astronomy Satellite (SAS-2). The spectrum of this radiation, which appears to be diffuse, is shown in Figure 1 to be made up of possibly two components with ~ 70 per cent of the radiation above 100 MeV to be of pion-decay origin. It is this predominant cosmic-ray nucleon induced component in the central region of the galaxy which we will discuss here, together with its implications for galactic cosmic-ray acceleration and propagation. Basic discussions of the physical processes involved in the production of pion-decay γ -radiation in the outer regions of the galaxy have recently been given by one of us (Stecker 1970, 1973).

II. LONGITUDE DISTRIBUTION OF THE GALACTIC RADIATION AND THE IMPLIED GALACTIC COSMIC-RAY DISTRIBUTION.

Kniffen, et al. (1973) also measured the longitude distribution of the galactic γ -radiation which they have shown to be confined to the galactic plane. This distribution exhibits a broad maximum in the longitude range $|\ell| \lesssim 30^\circ$ with possible edge maxima in the 20° to 30° range. Such a distribution can be expected of γ -radiation produced largely in a toroidal ring about the galactic center.¹ We therefore make the assumption that the γ -ray production rate along the gal-

¹A ring of increased cosmic-ray flux was suggested by Strong, et al. (1973) to explain the somewhat different results obtained by Kraushaar, et al. (1972) though, in that case, the ring was suggested to coincide with a region of postulated high magnetic field at 3.6 kpc.

actic plane in cylindrical coordinates $Q(r, \phi)$ is only a function of the distance from the galactic center, r . Taking as a boundary condition the fact that $Q(r)$ must be small for large r , it can be shown from the form of the data that $Q(r)$ must have a maximum at some value r_0 near $r_0/2$. We therefore choose to represent Q by a function of the form

$$Q(r) \propto r^x e^{-(r/r_0)^x}$$

The larger the value of the index x , the more confined the γ -ray production will be to a toroidal ring about r_0 . We find that a good fit to the observations is obtained by choosing the values $x = 8$ and $r_0 = 5$ kpc. Figure 2 shows the observational data together with the longitude distribution obtained from integrating $Q(r)$ along the line of sight in the galactic plane extending from the solar system at an angle ℓ from the galactic center. By using the values for the hydrogen density $n(r)$ given by Kerr(1969), Westerhout (1970) and Shane (1972), we can obtain an estimate of the implied spatial distribution of galactic cosmic rays $I(r) \propto Q(r)/n(r)$. This distribution is shown in Figure 3. It reflects only the distribution of cosmic rays in the 1 to 10 GeV energy range since it is these cosmic rays which produce almost all of the π^0 -mesons in the galaxy (Stecker 1973). Our results indicate that these "low-energy" cosmic rays have a maximum intensity in the region between 4 and 5 kpc from the galactic center

III. GALACTIC DYNAMICS

We do not find any obvious correlation between our deduced cosmic-ray distribution and the distribution of starlight in the galaxy (Perek 1962). If we assume supernovae to be the ultimate source of cosmic-rays, the increase in the number of supernova remnants in the 4-5 kpc region by a factor of about 2 (Iloviasky and Lequeux 1972) is not in itself sufficient to account for the increased cosmic-ray intensity in this region. It then seems reasonable to ask what else would make this region one of enhanced cosmic-ray intensity.

Investigations of 21-cm emission from the inner galaxy (Kerr 1969, Bok 1971, Van der Kruit 1971, Shane 1972, Sanders and Wrixon 1973) have indicated that the region inside 5 kpc contains hydrogen gas moving out from the galactic center with radial velocities between 50 and 200 km/s. The velocities are highest in the inner regions and decrease with increasing radial distance, becoming damped out by $\omega \approx 5.5$ kpc (Shane 1972). The maximum gradient in the radial velocity occurs at about 5 kpc. The region corresponding to the transition to non-radial motion, i.e., between 4 and 6 kpc, corresponds to a maximum in the density of galactic ionized hydrogen (Mezger 1970). All of these large scale features, as well as those indicated by the γ -ray observations, indicate that the region of the galaxy between 3 and 6 kpc is the

site of extraordinary large-scale galactic phenomena which are unique to this region and do not occur in the outer region of the galaxy.

According to the work of Roberts (1970) and Moore and Spiegel (1968), star formation can be triggered by an outward-moving shock wave which is strongest in the 4 to 5 kpc region. According to Moore and Spiegel (1968), this wave may be driven outward by hydromagnetic forces. The formation of young O and B stars in the region of maximum velocity gradient has been invoked to explain the formation of the ring of ionized hydrogen between 4 and 6 kpc (Mezger 1970). We suggest here that the increased low-energy cosmic-ray intensity in this region implied by the γ -ray observations may play a significant role in ionizing the hydrogen in this region.² The main expanding ring at $r \approx 4$ kpc may actually be oval shaped (Shane 1972) in such a way as to account for the asymmetry suggested in the SAS-2 γ -ray data!

IV. FERMI ENHANCEMENT

The picture of large-scale galactic dynamics outlined in the last section suggests that the γ -ray observations may reflect a cosmic-ray enhancement caused by the conversion of large scale hydromagnetic motion into cosmic-ray acceleration and enhancement. We suggest that the enhancement is caused by a coherent Fermi acceleration process (Fermi 1954) caused by compression of the cosmic-ray gas in the region between 4 and 5.5 kpc. Regardless of the exact details of this process, the net effect is an increase in energy of the particles given by the adiabatic compression relation, and an increase in the particle density caused by the trapping of particles in the compressed region.

²We thank Prof. George Field for this suggestion.

The total enhancement in the cosmic-ray intensity over the non-enhanced value in the solar neighborhood I_{\odot} is related to the mean acceleration time T_a by

$$\ln \frac{I}{I_{\odot}} = \ln \frac{q}{q_{\odot}} + \ln \frac{T_a}{T_{\odot}} + [(\Gamma-1)(\gamma-1)+1] \alpha T_a$$

where cosmic-ray differential spectrum is assumed to be of the form $KE^{-\Gamma}$. The quantity q/q_{\odot} which is the assumed increase in cosmic-ray sources, is taken to be 2 (see section III). The quantity T_a is defined as the time over which the cosmic-rays are accelerated (assumed equal to the escape time of cosmic-rays in this region) and T_{\odot} is the escape time of cosmic-rays in the solar vicinity, taken to be 3×10^6 yr. (O'Dell, et al. 1973). γ is the ratio of specific heats of the cosmic-ray gas and α is the specific compression rate, $-(1/V)dV/dt$, V being the volume compressed. $\alpha(\varpi)$ is given in terms of the expansion velocity of the gas $v(\varpi)$ by

$$\alpha = \frac{dv}{d\varpi} - \frac{v}{\varpi}$$

which is $\approx 2 \times 10^{-15} \text{ s}^{-1}$ for $\varpi = 5 \text{ kpc}$. For $I/I_{\odot} \approx 10$, we find that the cosmic-rays must be accelerated for a time $T_a \approx (7 \pm 1) \times 10^6 \text{ yr}$.

One prediction of this model is a relatively low cosmic-ray intensity in the region $\varpi < 3 \text{ kpc}$ due to deceleration and expansion effects. This ties in with the relatively low hydrogen density in the region inside 3 kpc (Oort 1970).

More detailed data on galactic γ -rays may be important in helping determine the detailed mechanisms behind galactic structure and

dynamics as well as propagation and trapping of cosmic-rays in the inner galaxy.

Acknowledgements:

We would like to thank C.E. Fichtel and D.A. Kniffen for discussions of the SAS-2 data and F.J. Kerr for discussions of the 21-cm hydrogen data.

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FIGURE CAPTIONS

- Figure 1 - Comparison of the SAS-2 (Kniffen, et al. 1973) spectral data on γ -radiation from the inner galaxy with a two component model based on 70% pion decay (Stecker 1970) and an E^{-1} integral Compton spectrum.
- Figure 2 - Comparison of the longitude distribution of galactic γ -radiation observed on SAS-2 with the distribution given by the theoretical model for $Q(\varpi)$ discussed in the text averaged over 10° intervals.
- Figure 3 - The un-normalized cosmic-ray distribution $I(\varpi) \propto Q(\varpi)/n(\varpi)$ deduced from our model describing the SAS-2 data.

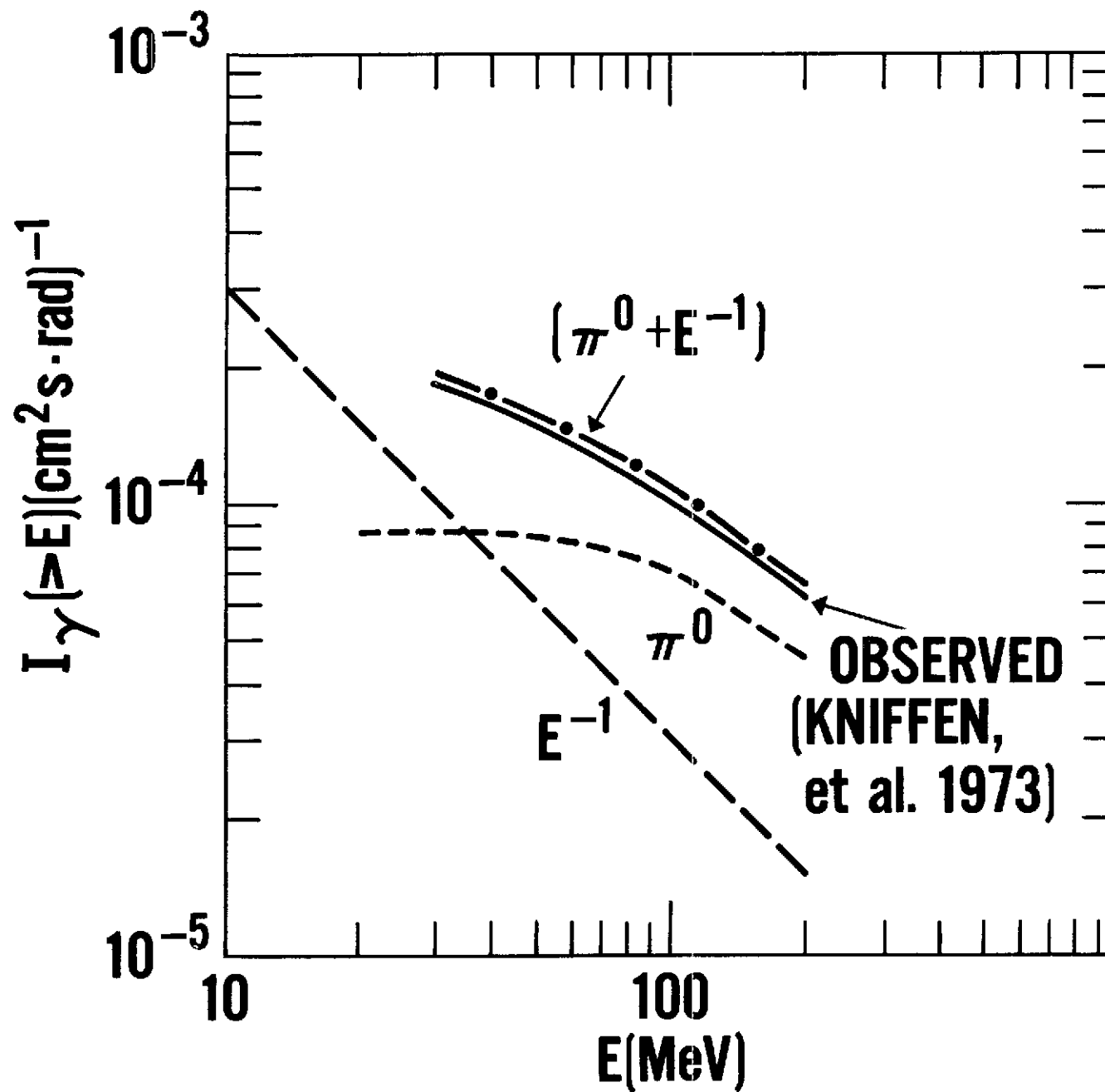


Figure 1

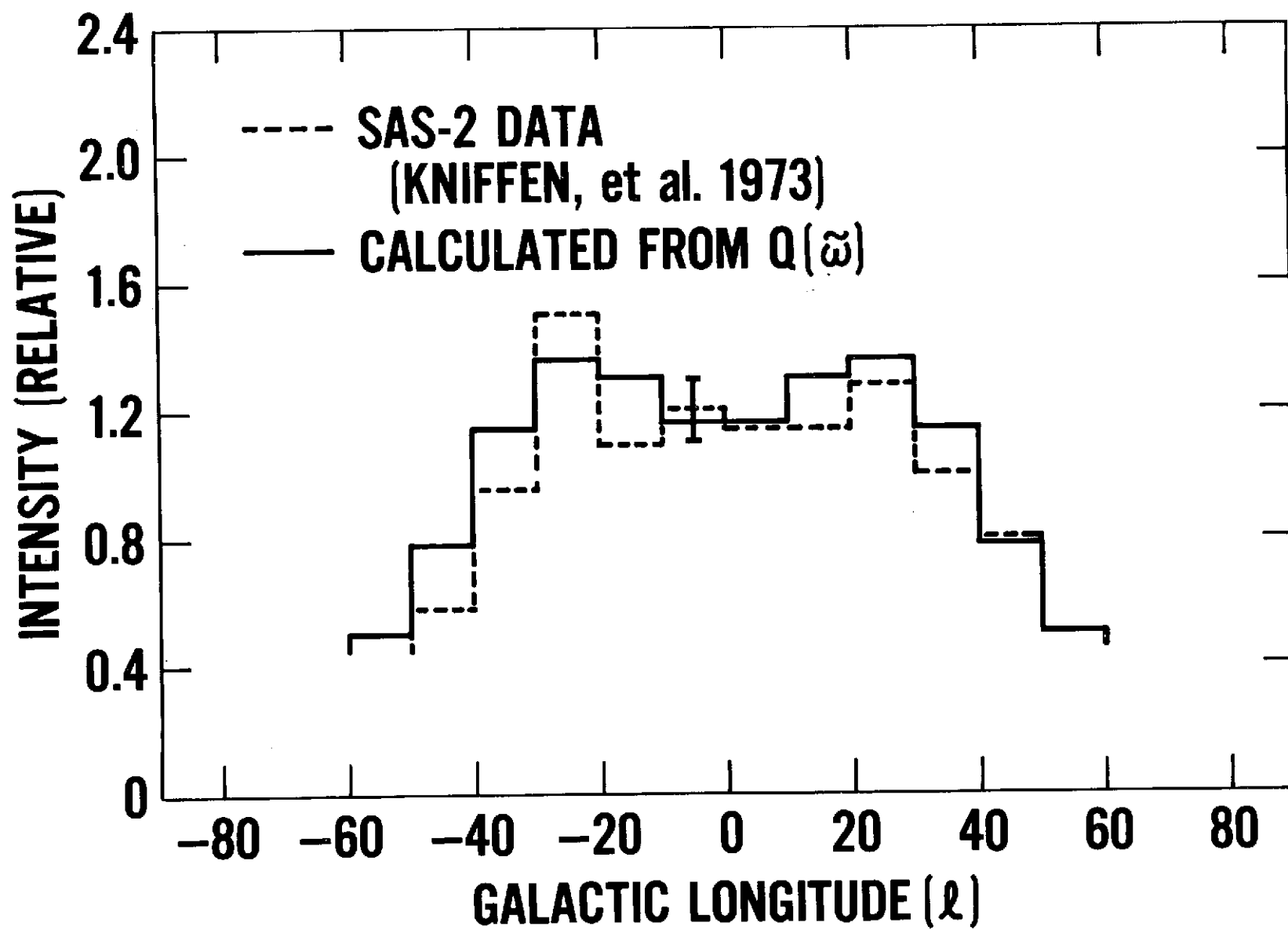


Figure 2

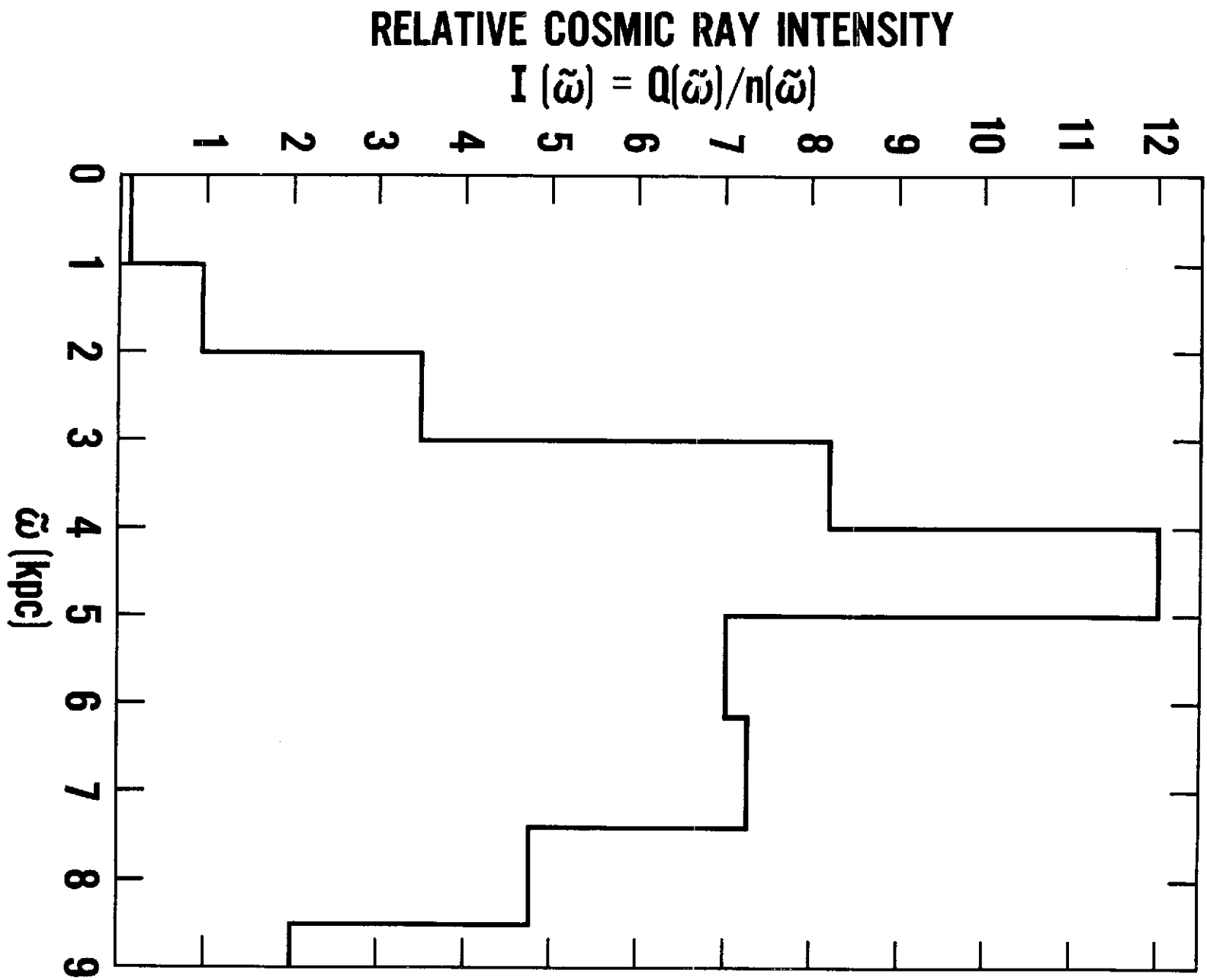


Figure 3